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Smart GNC Scheme for Autonomous Planetary Landing

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Abstract*: The moon or other nearest planets are important destinations for space science and the smart landing is key technology for exploring the different planets without fail. Due to the long round-trip delay of communication with the earth a pinpoint autonomous GNC (guidance-navigation-control) system will be suitable for precise landing. Hazard avoidance is another key issue for a safe landing of future planetary missions. Employing sensors and computers onboard, the lander detects hazards in the landing region, makes quick decision considering mission constraints within exigent time limit and generate trajectory to provide necessary command for guidance module that transfers the lander to a suitable safe landing site. Real time onboard terrain mapping Navigation and Guidance is one which has received much attention in the frame of planetary exploration. The paper illustrates the investigations concerning soft landing for planetary exploration and finally proposed a smart and autonomous GNC scheme based on real time range image measurements technique using laser range finder.*
Keywords: *Planetary landing; Autonomous; Hazard detection and avoidance*

I. Introduction

A several lunar or planetary missions were accomplished in last few decades; the guidance-navigation-control (GNC) technology is getting more important than ever. Because of long round-trip delay of communication with the ground station is extremely required to have the mission capability to perform precession autonomous GNC to the selected landing site [7]. With the help of a smart landing technique it will be possible to reach landing sites even in areas containing hazardous terrain features like craters, rocks or slopes. 2D and 3D solution of vehicle dynamics for lunar landing mission is developed by the author along with trajectory generation technique [10 - 14]. Now a scenario of smart GNC scheme is proposed in this paper for autonomous Planetary landing mission.

The arrangement of this paper is as follows. Outline of precession planetary landing including Earth-planet orbital transfer, planet orbit insertion and controlled descent are provided in the second section. Third section describes a summary of historical scenarios for successful soft landing. Traditional autonomous navigation and guidance methods for planetary landing are described in fourth section. Fifth section illustratesproposed smart landing technology for safe planetary landing and finally sixth section concludes the present investigation.

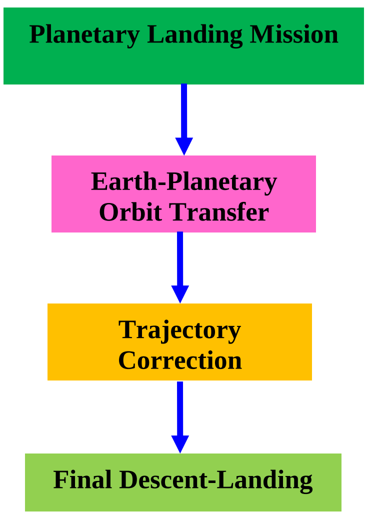

Fig.1. Mission flowchart

II. Smart Landing Mission Outline

From Earth to planetary journey of mission consists three main phases such as transfer, insertion and descent. After spacecraft is launched it enters in to the planetary circular orbit with the help of several mid-course trajectory corrections. Before starting descent, the spacecraft executes burning sequences anti-parallel direction to its velocity in order to perform some important orbit maneuvers and reaches at the point of closest approach that places the vehicle in to lower planetary orbit. Then the spacecraft will start descent phase to land at the specified landing site on the planetary surface with in the allowable error range.

At the end of trajectory correction, Hohmann transfer brings the spacecraft to its lower most suitable orbit. Although Hohmann transfer is most economical but when the semi-major axis of the final orbit is more than about 12 times greater than that of the initial orbit, a bi-elliptical transfer is even more economical. After orbital injection, descent starts to accomplish pin-point landing and performs several successive steps within limited time constraint. Figure 2 shows the different steps during landing. First step is the deceleration step, from 15 km to 1km altitude above the planetary surface. In this step proportional velocity of the landing vehicle to the planetary surface will fall from 1 km/s or so lower velocity.Employing sensors and computers onboard the lander performs terrain mapping, detects hazards in the landing region, and makes quick decision considering mission constraints. It is a very challenging task to develop 3D map for navigation system which will enable to estimate the present state of lander and selecting the suitable landing site using information provided by range imaging. Extracting the hazard free safe landing site by executing developed algorithm the lander could generate trajectory. Guidance module follows that trajectory performing translation towards appropriate landing site to avoid hazardous terrain features like craters, rocks or slopes. Due to the fast dynamics of this descent step, the requirements in terms of computation speed are quite stringent. The fourth step is the free terminal descent step to conclude the pin-point touchdown episode.

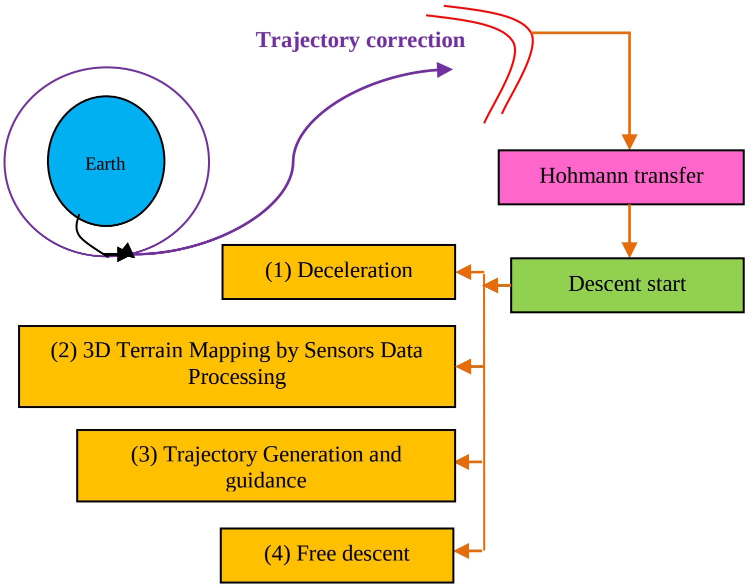

Fig.2. Different sequences of planetary smart landing

III. Successful Landing Missions

Since 1959 several missions of spacecraft landing has been accomplished on other planets and bodies in the solar system such as Moon, Venus, Mars, Eros, Jupiter, Titan, Comet 9P, Itokawa and Enceladus. Some of them were successful soft landings and rests are both intended and unintended crash-landings explored by USSR, USA, Japan.ESA, China and India at different period of time. Exploring the surface of other celestial body, Moon has got especial attention. *Lunar Prospector*, the last lunar surface exploration operation in 1999 by USA, has ended 24th spacecraft landing mission on Moon since 1962 starting with *Ranger 4* to produce hard impact on the Moon intentionally but it hit on lunar far side due to failure of navigation system. In 1959, USSR sent the first spacecraft *Luna 2* to reach the surface of the Moon, and it impacted the lunar surface west of Mare Serenitatis near the craters Aristides, Archimeded and Autolycus. USSR completed their 14th spacecraft landing mission on Moon by *Luna 24* in 1976 with robotic sample return task. Following *Luna 2*, USSR carried several unsuccessful landing missions till to achieve first successful soft landing on Moon in 1966 by *Luna 9* transmitting first photographic data from the surface of another planetary body to Earth. Just four months after the landing of soviet *Luna 9* mission, *Surveyor 1* landed on an extraterrestrial body, Moon, as first soft landing American spacecraft. This spacecraft was launched in 1966 directly in to a lunar impact trajectory and at a height of 3.4 m above the lunar surface the engines were turned off to let the spacecraft freely touchdown on the surface. Following *Surveyor 1,* USA completed 6 manned missions of 11 successful soft landings on lunar surface while human carried lunar rover during last 3 manned missions to the Moon surface. On the other hand USSR never carried out successful manned mission towards Moon instead 7 successful unmanned soft landing missions on lunar surface including 3 robotic sample return and 2 robotic lunar rover missions. In 1993 and 2006, Japan and ESA respectively launched lunar orbiter and both were intentionally impacted on lunar surface at end of missions. In 2013 – Chang'e3 - first soft-landing vehicle since 1976, and lunar rover is deployed by China.

In the next month of first successful soft landing on lunar surface by USSR, *Venera 3,* the first spacecraft to land on another planet, was launched by Soviet Union to explore the surface of Venus but the mission was unsuccessful, and crash-landed on Venus on March 1, 1966. Among Venera series of probes to Venus, *Venera 7* was the first man-made spacecraft to successfully land on a different planet to transmit data from there back to Earth. In 1985 USSR concluded Venus mission performing 10th successful soft landing by

Vega 2 landed on Venusian surface. For Venus, USA conducted Pioneer mission consisted two separate launch; *Pioneer Venus 1 & 2.* Pioneer Venus 2 sent four small probes into the Venusian atmosphere in 1978. None of these atmospheric probes had designed for soft landing except the large probe had a parachute that was designed to cut loose at a certain altitude. All the probes sustained till impact on Venusian surface, but only one probe survived for a considerable period after impact.

Mars 2 and *Mars 3* are the first probes impacted on Mars launched by Soviet Union. Both of these two probes were carrying lander and failed upon landing. *Mars 3* was the only soviet lander which was able to send signal for 20 seconds after landing till 1971 and in 1974 *Mars 6* lost the contact at landing. The first successful soft landing was performed by American landers *Viking 1 & 2* in 1976 on Mars. To prove the slogan, "faster, better and cheaper", USA was able to land successfully *Mars Pathfinder* and *Sojourner Rover* in 1997 with three years of development and at one fifteenth the cost of *Viking* mission. It executed different investigations on the Martial soil and lasted almost three months. *Mars Polar Lander* was launched to touch down on the southern polar layered terrainbut because of an unknown reason communication was lost just prior to atmospheric entry in 1999. *Beagle 2* was first European lander designed to explore the Martian surface and sub-surface and carried by *Mars Express* "mother ship" in 2003 but lost contact after taking attempt for soft landing. *Spirit* and *Opportunity* are two rovers of NASA's Mars Exploration Rover Mission, landed successfully in 2004 on Mars surface. The latest successful landing mission on Mars was a robotic spacecraft *Phoenix* under the Mars Scout Program and landed successfully on May 25, 2008 near the edge of landing ellipse, little far (25-28 km) from predicted landing position. On November 10, 2008, the mission was declared concluded after NASA's engineers were unable to contact the lander.

As one of the large Near Earth Asteroids, *Eros* was visited by American probe *NEAR Shoemaker* which was launched in 1996. Primary goal of the mission was to study from a circular orbit with a radius of 200 km, gradually it was altered to 35 x 35 km retrograde orbit in December 2000 and finally two months later the probe landed on the asteroid's surface using its maneuvering jets at the end of its mission. NASA studied the planet *Jupiter* and its moons launching an unmanned spacecraft *Galileo* in October, 1989 by the space shuttle *Atlantis*. A little more than six years later it arrived at Jupiter in December 1995. After 14 years in space including 8 years of service in the Jovian system, the probe was intentionally directed into Jupiter's atmosphere to impact on a planetary body. The *Huygens* probe was an atmospheric entry probe carried to Saturn's moon *Titan* launched in October, 1997 as part of the *Cassini-Huygens* mission conducted by ESA, USA and Italy. 20 days after separation from *Cassini* orbiter, *Huygens* landed on Titan in January, 2005 near the Xanadu region. To study the composition of the interior of the *Comet 9P*, NASA launched impactor, *Deep Impact* in January 2005. In July, 2005, it successfully impacted on *Comet 9P* and returned images as late as three seconds before impact. To return a sample of material from *Itokawa,* a small near-Earth asteroid, JAXA launched an unmanned spacecraft, *Hayabusa* in 2003. Upon arrival at *Itokawa, Hayabusa* studied the asteroid's shape, spin, topography, color, composition, density and history then it attempted to land in November 2005 but the landing was unsuccessful and sampling chamber was sealed. Finally the spacecraft is scheduled to return to Earth by June 210. Moreover, *Hayabusa* was carrying a detachable lander, *Minerva mini-lander* but it failed to reach the surface due to an error during deployment.

IV. Investigations for Pinpoint Landing

Landing error ellipse is currently characterized for descent and landing for missions is roughly greater than 30 x 100 km. But the GNC method is used for such achievement with out considering any terrain recognition or hazard avoidance mechanism. After extensive search it is found that among successfully flown automated landing systems for other planets, none had a terrain-relative GNC system for pinpoint landing. MER is the only mission used descent image motion system to estimate horizontal velocities but it had neither terrain recognition nor hazard avoidance capabilities. Its image motion estimation system was equipped with a descent imager, a radar altimeter, an inertial measurement unit and an algorithm to provide a solution for horizontal velocity estimation problem which helped for air bags deployment during touchdown. The prominent space agencies like NASA, ESA, JAXA etc. are planning to demonstrate an ambitious capability which is pinpoint landing to another planetary body. According to the ongoing research of NASA's Jet Propulsion Laboratory, a pinpoint landing is characterized to meet future mission requirements delivering a spacecraft to bellow 100 meters of a targeted landing site [3, 8]. In order to achieve this, several new technologies are on the line to be developed over the coming few years. Some researches are already conducted and some are in planned. Following discussion presents an overview of these developing technologies.

Topographic recognition and fixation point extraction: Currently vision is the most effective sensory in precise space exploration which can give us information on structure or shape of observed target. At the end of last century, researchers of JAXA proposed 2 key technologies; firstly a direct extraction scheme of desired geographic feature from a gray scale image of a target landing site and secondly a fixation point tracking scheme extracted from image taken by navigation camera which determines relative position between the target point and the spacecraft (Misu et al 1999) [1]. Image based Extended Kalman Filter (EKF) is implemented in this research. In topographic recognition scheme it is shown to achieve feasibility and robustness even without detailed information about the target albedo and illumination environment. In their method a look-up table is formed in advance by various indexes of different geographic categories then the calculated index of featured image will be matched to obtain the exact geographic category. The index of conformity is calculated with the help of observed reflectance and the normal directions. To determine appropriate target site of landing, a fuzzy logic is used. In fixation point tracking, author employed block-matching algorithm to estimate relative position between target point and spacecraft. If there is failure of fixation point tracking then the next image is expected and a new fixation point is re-extracted in order not to loose the target point.In this investigation Euler angles are used for spacecraft attitude parameterization. But the use of quaternion rotation increases the robustness because unlike the Euler angles, the quaternion has no singularities.

Landmark based topography determination: Landmark is defined in terms of local topography and albedo maps in a local coordinate system with unit vectors in three directions. Firstly data is extracted for a set of image space locations for a number of landmarks in a number of images. Then a multi-dimensional estimation for the locations of all landmarks and the camera locations and the orientations for all of the images are performed by iteration process. While the landmarks are aligned closely enough to within a few percent of the size of the map, then the map projected brightness of that image is fit to a simple function of slop and that enabled to determine height [2]

Landmark based spacecraft position estimation during landing: Craters are common on the surface of planets, satellites, asteroids and other solar system bodies. It is found landforms and generally bowl shaped with simple and unique geometry which can be considered as ideal landmarks for selecting the targeted landing site. Yang et al has investigatedcrater basedposition estimation of spacecraft localization for pinpoint landing on Mars [3]. With in pre selected landing ellipse craters are mapped in terms of landmarks on Earth using orbital imagery and using these nominal data lander determines landing site onboard. During descent geometric recognition technique is used to match craters extracted from current images to a previously created database. From these match landmarks the position and orientation of the spacecraft is estimated with respect to the surface of the planetary body.

V. Proposed Smart GNC Scheme

Safe landing is the key issue for planetary landing mission on an unknown terrain and to achieve this hazard is the main obstacle. Either of two design approachesis essential for safe landing in which one is hazard tolerance and second is hazard avoidance. Preceding lander missions to the surface of the moon and other planets have used no-autonomous and hazard tolerant designs rather used physical means to protect the payload from a shock of impact on the surface. Employing airbags by Mars Pathfinder is an example of hazard tolerant design. In Hazard avoidance the spacecraft needs to use onboard hazard detecting instrumentin the landing zone and maneuvering capabilities of landing selecting an alternate site if necessary. Therefore, hazard avoidance is an important aspect of future landing missions to make possible landing even in such areas that are not flat and hazard free as the nominal selected landing sites of the current exploration missions.

Our smart landing technology proposes an autonomous, high-speed, real-time and environment-adaptive GNC algorithm toward a designated and scientifically attractive landing site on unknown planetary body by terrain mapping and hazard classification using laser range finder. Our ongoing developing algorithm will be able to generate 3D terrain maps and classifies different hazardous object like craters, high slopes, shadows, boulders, mountain, valleys etc to detect navigable and non-navigable regions.There are some functional requirements for this new technology.

1. Unlike the previous missions [3] the proposed system must be able recognize completely new terrain of other planet because future exploration missions envisage landing on planetary surfaces that are not known a prior.
2. The system should not only be able to detect hazards, but also to decide about area which is deemed to be secure for landing and guide the spacecraft towards that safe area. Moreover, the system is responsible to select the reachable landing site. This attainability will be achieved considering mission constraints such as available onboard propellant and thruster characteristics.
3. The system must accomplish the task under extreme time constraints. For data collecting from range finder, processing, mapping, identifying the navigable and non-navigable region, other sensors' data infusion, decision making, final trajectory generation and lastly provide guidance toward the final destination should be done in a few second.The phase of spacecraft localization starts between heat shield separation and powered descent phase. There is a roughly 60 second window of opportunity to send the spacecraft to its perfect landing site at low gate from high gate [3]. Therefore, it is a very challenging requirement. On August 25, 2008 Tokyo based *Renesa Technology Corporation* announced a news regarding successful fabrication of high speed processor that realizes processing performance of up to 8620 million instructionsper second (MIPS). However it demands for further investigation to cope with the proposed smart landing technology.

An integrated simulation tool is being developing which contains different modules that interact according to the block diagram shown in Figure 3.

Generating 3D Point Cloud: Our approach for smart landing uses lander equipped with 2D laser range finders. At high gate position range information generates a 3D point cloud onboard and ultimately this cloud models the terrain.

Terrain Mapping: Terrain map can be generated once pose estimation and range information are available. Accurate pose estimation technique uses IMU and the attitude quaternion. IMU is the major measurement element particularly during orbit maneuver and soft landing phase. IMU includes gyros and accelerometers and it is one of the key units for GNC system. GNC sensor data from other sensors, such as, sun sensors, horizon sensors or radar can be easily included in the filter to improve attitude and position estimation. Pose information and laser finder data will be projected into 3D Cartesian space implementing standard geometry.

Terrain Modeling: Our Terrain algorithm is organized based on Markov statistical model and it divides the terrain into two areas: navigable and non-navigable areas. Lander considers the comparatively flat surface as navigable areas for safe landing. Non-navigable area classifies the terrain into different sub categories. These are actually called hazardous area like craters, high slopes, shadows, boulders, mountains, valleys etc to be avoided. Eventually the maps generated by the algorithm will clearly show the areas where lander can retarget for safe landing and the areas considered unsafe for landing.

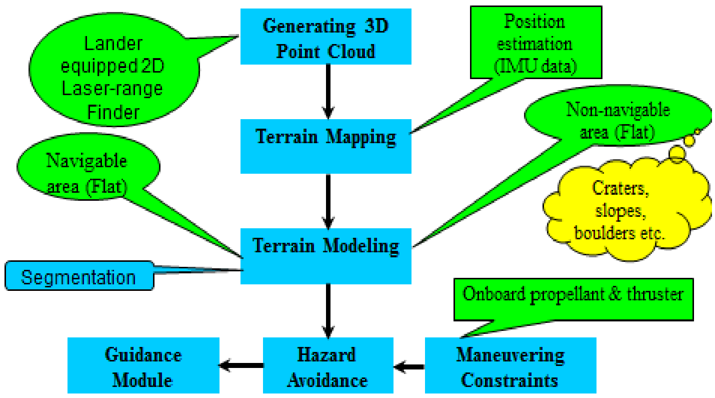

Fig.3. Block diagram of smart landing technology

Segmentation: Due to sensors noise it may turn out that some part of the map is not properly classified and these errors exist in a small part of the terrain map. Implementing Markov Random Fields segmentation technique those errors can be fixed [5]. Basically by this Markov technique the probability distribution for each segmented cell is précised conditionally with the probability distribution of its neighbor cells.

Hazard Avoidance: According to the algorithms to be developed that will estimate the specific locations and elevations of surface hazards building 3D elevation map. For navigable flat terrains, generated points by the range sensor are expected to be well aligned, with a minimal variance in altitude. On the other hand, the hazardous areas are rough terrain where 3D points are not properly aligned even with large variance in altitude. Before choosing appropriate landing site finally, some maneuvering constraints will be considered like available onboard propellant and thruster attainability. Keeping everything in account, algorithms will select the safe landing location and will pass to the lander guidance module that produces a trajectory to the retargeted landing site.

Guidance: Guidance is the function to transfer the lander from any current state to touchdown. In our research, an adaptive guidance algorithm will be developed based on E-Guidance [6] to redirect the lander by selecting a retargeting landing site.

VI. Conclusion

Precisely landing on other planetary bodies at rough and unknown terrain but scientifically significant is a difficult and risky task. A smart landing technology consisting real time autonomous terrain mapping, efficiently hazards identification, avoiding hazards and trajectory generation towards safe landing site is crucial. In this paper, laser range finder based a smart autonomous landing scheme for unknown planetary body exploration has been suggested. Our proposed algorithm to be developed will be able to build 3D terrain maps classifying safe landing sites and different specified hazardous objects and finally to make safe pinpoint landing trajectory to command guidance module considering required mission constraints within challenging time limit.

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References

[1]. Misu, T., Hashimoto, T., Ninomiya, K., "Optical Guidance for Autonomous Landing of Spacecraft", IEEE Transactions on Aerospace and Electronic Systems Vol. 35, no. 2, April 1999.

[2]. Robert W. Gaskell, "Determination of Landmark Topography from Imaging Data", 25th Annual AAS Guidance and Control Conference, Vol. 111, pp. 167-180, 2002.

[3]. Yang, C., Adnan, A. "Land mark based position estimation for pinpoint landing on Mars", Proceedings of the 2005 IEEE International Conference on Robotics and Automation Vol. 22, Issue 22, pp. 4470-4475, 2005.

[4]. Nasab, N. M., Analoui, M., Delp, E. J. "Robust and efficient image segmentation approaches using Markov random field models." In Journal Electronic Imaging, Vol.12, No.1, pp. 50-58, 2003.

[5]. Kindermann, R., Snell, J. L., "Markov Random Fields and Their Applications." Contemporary Mathematics, American Mathematical Society, 1980.

[6]. Cherry, G.W., "E Guidance – A General Explicit, Optimizing Guidance Law for Rocket Propelled Spacecraft", AIAA, paper no. 64-638, 164.

[7]. Steven N. Rader, Marcum L. Reagan, Barbara Janoijo, and James E. J., "Human-in-the-Loop Operations over Time Delay: NASA Analog Missions Lessons Learned" Technical report, NASA Johnson Space Center, Houston, TX, 2012.

[8]. Yu, M., Cui, H.T., Tian, Y., "A new approach based on crater detection and matching for visual navigation in planetary landing", Advanced Space Research, 53 (12), 1810–1821, 2014.

[9]. Wang, D., Huang, X., Guan, Y., "GNC system scheme for lunar soft landing spacecraft", Advanced Space Research, 42 (2), pp. 379–385, 2008.

[10]. Mehedi, I. M. and Kubota, T., "Advanced Descent Scheme for Lunar Landing", Automatic Control in Aerospace – Online Journal, Vol. 4, No.1, 2011.

[11]. Mehedi, I. M. and Kubota, T., "Advanced Guidance Scheme for Lunar Descent and Landing from Orbital Speed Conditions", Transaction of Japan Society for Aeronautical and Space Sciences (JSASS), Vol. 54, No.184, pp. 98-105, 2011.

[12]. Mehedi, I. M., Kubota, T., "Trajectory Generation Scheme for Precise and Safe Lunar Landing", Journal of Space Engineering, Vol. 4, Issue 1, pp.1-13, 2011.

[13]. Mehedi, I. M., Kubota, T. Al-Saggaf, U. M., "3-Dimensional Analytical Solution for Lunar Descent Scheme", Iranian Journal of Science & Technology, Transactions of Electrical Engineering, Vol. 39, pp.67-77, 2015.

[14]. Mehedi, I. M., Kubota, T. Al-Saggaf, U. M., "3-Dimensional advanced solution for lunar descent and landing", Journal of Vibroengineering, Vol. 17, Issue 1, pp.527-543, 2015.